Review

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Review

Nutrient Utilization, Requirements and Nutrigenomics in Sheep and Goats

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Simple Summary: History, progress and pertinent issues of nutrient requirements of sheep and goats were presented and discussed. Mathematical models and conversion efficiencies used by the National Research Council to predict nutrient requirements in sheep and goats have been highlighted to persuade further research and discussion for the purpose of refinement of these nutritional standards. Nutrigenomics, artificial intelligence, precision nutrition, and other advanced methodologies were identified for their implications in the future development and a more precise estimation of nutrient requirements in sheep and goats.

Abstract: The most recent National Research Council Nutrient Requirements for Sheep and Goats was published in 2007, one of the most consequential nutrient requirement recommendations for sheep and goats in the world. It is pertinent to continue the refinement and discussion of nutrient utilization and requirements for the purposes of enhancing the efficiency of production systems, maximizing resource economy, and minimizing the carbon footprint, among others. Progress has been made in the estimation of energy and protein requirements in sheep and goats, mainly utilizing empirical feeding experimentation, comparative slaughter technique and minimum endogenous loss method. In sheep, newer estimates of energy and protein requirements for maintenance and growth and partial efficiencies had been reported since 2007. There were suggestions that energy and protein requirements could have been affected by breed, wool growth, gender and size; with these reported values being similar or lower than the recommended values in international feeding systems such as NRC, ARC, INRA and AFRC. In goats, energy and protein requirements for growing goats were reported to be either higher or lower than the established recommendations, depending upon meat or dairy breeds. Effect of gender on energy requirement appeared to be related to the stage of growth or degree of maturity. Newer data also suggested that the guidelines of the major feeding systems for the entire growth phase may not be adequate for non-pregnant and non-lactating pubertal females. In multiparous pregnant goats, energy and protein requirements for maintenance did not appear to be affected by days of pregnancy, but efficiencies of metabolizable energy and metabolizable protein utilization for pregnancy were. There were suggestions that that metabolizable protein synthesis in the rumen can be predicted from energy intake using combined equations that encompass both sheep and goats, but more data on goats were called for to account for specific differences in nutrition. In addition to sulfur, there has been progress made on the estimation of maintenance and growth requirements of calcium, phosphorus, potassium and magnesium in goats, with suggestions on the consideration of gender and breed differences. Species, level of Intake, genotype, mature size, age, gender, body composition, use of tissue energy, activity, season, and acclimatization continue to be important considerations for the estimation of nutrient requirements in sheep and goats, with emerging factors such as climate change, heat stress, parasitism and secondary plant compounds. Model equations and partial efficiencies used by NRC to predict energy and protein requirements for maintenance, growth, lactation, and fiber have been highlighted and discussed for the purpose of a more focus discussion and refinement for the future. Potential and limitation of both traditional and emerging methodologies in determining the nutrient requirements in sheep and goats were discussed. To justify the research investment, emerging methodologies such as nutrigenomics will have to be linked more directly to the improvement of production efficiency via more precise prediction of nutrient requirement.

Keywords: sheep; goat; nutrient requirement; nutrient utilization; nutrigenomics

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1. Introduction

The economic and social impacts of sheep and goat production in the improvement of living standards and alleviation of poverty in rural communities are recognized throughout the world [1]. Understanding nutrient utilization by sheep and goats enhances the efficiency of production systems, maximizes resource economy, and minimizes the carbon footprint. Nutrient requirements can be one of the most important considerations for the precision nutrition [2] in sheep and goat production. Requirements and utilization of structural and nonstructural carbohydrates, degradable and bypass proteins, lipids, minerals, and vitamins are essential parts of this important scientific understanding. Nutrient requirements are affected by multiple factors such as individuality, genetics, climates, diet, age, and physiological stages [3], and a continuous update of knowledge is essential. Relatively recent advancements in nutrigenomics [4–7] have led to improved knowledge on the molecular interaction between nutrients and other dietary bioactive components with respect to the genome, effect of food constituents on gene expression, and influence of genetic variation on nutrition; therefore, contributing to a better understanding of nutrient utilization and requirements. Such understanding allows optimizing and customizing nutrition with respect to a subject's genotype and offers great potential for a more precise determination of nutrient requirements in sheep and goats. The most recent National Research Council (NRC) Nutrient Requirements for Sheep and Goats was published in 2007 [3]. It is pertinent to continue the refinement and discussion of nutrient utilization and requirements in sheep and goats from the perspectives of traditional nutrition and nutrigenomics. As an introductory article for the special issue on "Nutrient utilization, requirements, and nutrigenomics in sheep and goats", the objective of this paper is to provide an overview of the progress in establishing nutritional standards through traditional research in nutrient utilization and nutrient requirements, but also considering new approaches such as precision nutrition and nutrigenomics.

2. National Research Council and History of Nutrient Requirements in Sheep and Goats

The National Research Council was organized in 1916 under a congressional charter requested by then President Wilson of the United States [8]. It is the operating arm of National Academy of Sciences, National Academy of Engineering, and Institute of Medicine; with the purposes of improving government decision and public policy, increasing public understanding, and disseminating knowledge in science, engineering, technology and health. The National Research Council supports studies in six divisions including Earth and Live Sciences. The Division of Earth and Live Sciences conducted studies and publishes "Nutrient Requirements of Animals". Under the Division of Earth and Live Sciences, Board on Agriculture and Natural Resources approves nutrient requirements of various animal species upon the recommendation of Committee on Nutrition and Subcommittee of Nutrition of various animal species.

The 1st Edition of Nutrient Allowances for Sheep was published by NRC in 1945 [9] and was revised in 1949 [10], 1957 [11], 1964 [12], 1968 [13], 1975 [14], with the 6th revised Edition published in 1985 [15]. The 6th revised Edition [15] was the last published NRC recommendations solely focusing on sheep. The 1st Edition of Nutrient Requirements of Goats was published by NRC in 1981 [16]. Since the NRC published its 1st Edition of Nutrient Requirements of Goats, there has been advancement in research pertaining to energy and protein [17–22] and sulfur [23–29] requirements in milk, meat and fiber producing goats that may or may not have been considered fully in the most recent NRC publication on nutrient requirements of goats [3]. A series of articles pertaining to energy and protein requirements in goats [30–34] were published prior to and considered in the 2007 NRC publication [3]. The latest version of nutrient requirements for sheep and goats combinedly appeared in "Nutrient Requirements of Small Ruminants: Sheep, Goats, Cervids and New World Camelids" and was published sixteen years ago [3]. Incorporated in the 2007 publication were the concepts of ruminally undegraded protein and microbial crude protein as sources of metabolizable protein (MP). For large ruminants, "Nutrient Requirements of Beef Cattle" and " Nutrient Requirements of Dairy Cattle have been revised and published more recently [35,36]. "Nutrient Requirements of Animals" is considered one of the most important nutritional standards once published. They are commonly used as a standard for future animal experiments, and NRC recommendations are among the most cited publications in animal nutrition. They can be considered as the culmination of nutritional accomplishment at a particular time period.

In addition to NRC, there are other notable international nutrition standards for sheep and goats that have been recommended by the Agricultural Food and Research Council in the United Kingdom [37–40], the Instituto National de la Recherche Agronomique in France [41–43], and the Commonwealth Scientific and Industrial Research Organization in Australia [44,45]. Most of these recommendation predated the most recent NRC recommendation for sheep and goats [3]. Nutrient requirements of meat-type sheep and goats were revised in China, after a decade-long coordinated national effort utilizing comparative slaughter trial, digestibility trial, and carbon–nitrogen balance technique [46].

3. Energy and Protein Requirements in Sheep

Since 2007, there have been progress made in the estimation of energy and protein requirements for maintenance and growth in sheep. Galvani et al. [47] conducted comparative slaughter experiment using Texel crossbred lambs (n = 30) and reported that net energy (NE_m) and metabolizable energy requirements for maintenance (ME_m) were 58.6 and 91 kcal/kg $^{0.75}$ of shrunk body weight (SBW), respectively. Partial efficiency of energy use for maintenance was calculated to be 0.64. Net energy requirements for growth (NE_g) of lambs at 15 and 35 kg of SBW with an average daily gain (ADG) of 250 g were calculated to be 424 and 553 kcal/d, respectively. Partial efficiency of energy use for growth was calculated to be 0.47. To estimate protein requirements by endogenous nitrogen (N) loss in Texel crossbred lambs [48], the growth pattern of the wool was found to influence protein requirements and the estimated growth requirements were lower than those reported by the most nutritional systems. They reported that net protein requirement for maintenance (NP_m) was 1.52 ± 0.18 g/kg $^{0.75}$ of SBW, metabolizable protein requirement for maintenance (MP_m) was 2.31 g/ kg $^{0.75}$ of SBW, and the efficiency of MP use for maintenance was 0.66. Net protein requirements for body weight gain (NP_g) and wool growth (NP_w) of lambs at 15 and 35 kg of SBW, with an ADG of 250 g, were 28.7 and 27.3 g/day and 3.8 and 5.8 g/day, respectively. Estimated efficiencies of MP use for body weight gain (k_{pg}) and wool growth (k_{pw}) were 0.71 and 0.46, respectively. Salah et al. [49] conducted a meta-analysis study of 590 publications and concluded that energy and protein requirements of tropical and warm-area ruminants compared with those proposed in the international feed system standards such as the NRC, ARC, INRA and AFRC tables were higher and little or no differences between species were found.

Comparative slaughter and digestion trials were conducted on Dorper × Hu crossbred lambs to determine energy and protein requirements [50]. Energy and protein requirement for growth in growing lambs were founded to similar to the NRC recommendations for early and later maturating growing sheep. They reported that ME_m (400.61 ± 20.31 vs. 427.24 ± 18.70 kJ kg^{-1} /SBWkg$^{0.75}$), partial efficiency of ME utilization for maintenance (k_m, 0.64 ± 0.02 vs. 0.65 ± 0.03), partial efficiency of ME utilization for growth (k_g ; 0.42 ± 0.03 vs. 0.44 ± 0.02), and NP_m (1.83 ± 0.17 vs. 1.99 ± 0.28 g kg^{-1} of SBW$^{0.75}$) did not differ due to gender. They also reported that rams had higher NP_g (15.9 to 44.3 g d^{-1}) than those of ewes (13.07 to 33.0 g d^{-1}) at the similar condition of BW and ADG. Oliveira et al. [51] suggested that total ME and MP requirements were lower than those recommended by the NRC and AFRC from a meta-analysis of seven experiments (n = 243) and proposed new equations for nutrient requirements of hair sheep raised in tropical regions. A comparative slaughter experiment on a hair sheep breed Santa Ines lambs (n = 38) suggested that the importance of updating the tables of international committees and of including data obtained from studies with sheep breeds raised in tropical conditions, with the purpose of improving the productive efficiency of the animals [52]. They reported that NE_g varied from 1.13 to 2.01 MJ/d for lambs with BW of 15 and 30 kg and ADG of 200 g. The calulated NP_g varied from 24.6 to 16.3 g/d for lambs with BW of 15 and 30 kg with ADG of 200 g. The calculated metabolizable energy efficiency for gain (k_g) was 0.37, and the metabolizable protein efficiency for gain (k_{pg}) was 0.28. The NE_m and NP_m did not differ between castrated and non-castrated lambs, with values of 0.241 MJ/kg FBW$^{0.75}$/d and 1.30 g/kg FBW$^{0.75}$/d, respectively. The metabolizable

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energy efficiency for maintenance (k_m) was 0.60, and the efficiency of metabolizable protein for maintenance (k_{pm}) was 0.57.

Pereira et al. [53] conduct a comparative slaughter experiment to evaluate the energy and protein requirements of intact male, castrated male and female Morada Nova lambs (n = 47). For all sexes, the NE_m was 73.0 kcal/kg$^{0.75}$ empty body weight (EBW)/d. The metabolizable energy efficiency for maintenance (k_m) was 0.58. The metabolizable energy efficiency utilization for gain (k_g) was 0.36; 0.25 and 0.28 for intact males, castrated males and females, respectively. The NE_g was 0.191, 0.198 and 0.276 Mcal/kg$^{0.75}$ EBW/d for intact males, castrated males and females, respectively, with a BW of 20 kg and a ADG of 100 g and differed between sexes. The NP_m and MP_m were 1.06 g/kg$^{0.75}$ BW/d and 3.46 g/kg$^{0.75}$ BW/day, respectively and the NP_g differed between sexes. The NP_g was 7.08, 7.11 and 6.78 g/d for intact males, castrated males and females, respectively, for animals weighing 20 kg and with ADG of 100 g/d. They concluded that net energy and protein requirements for maintenance of Morada Nova lambs slaughtered between 15 and 28 kg did not vary by sex, and NE_g increases and NP_g decreased with the increase in body weight in hair lambs. Mendes et al. [54] utilized 35 crossbreed Doper x Santa Ines lambs in a slaughter experiment to estimate energy and protein requirements for maintenance and growth and concluded that NE_m for crossbreed Dorper × Santa Ines lambs was similar to those recommended by the international committees but NE_g was lower.

4. Energy and Protein Requirements in Goats

Since 2007, there are a number of articles published pertaining to energy and protein requirements in goats. To determine the energy and protein requirements for maintenance and growth using 34 ¾ Boer × ¼ Saanen crossbred, intact male kids [55], the NE_m was reported to be 77.3 kcal/kg$^{0.75}$ EBW or 67.4 kcal/kg$^{0.75}$ SBW. The ME_m were 118.1 kcal/kg$^{0.75}$ EBW or 103.0 kcal/ kg$^{0.75}$ of SBW. These requirements were calculated by iteration assuming that the heat produced was equal to the ME intake at maintenance. The partial efficiency of the use of ME for NE for maintenance was 0.65. The NP_m was 2.44 g / kg$^{0.75}$ EBW. The NE_g ranged from 2.55 to 3.0 Mcal/kg of EBW gain at 20 and 35 kg of BW, and NP_g ranged from 179 to 185 g/kg of EBW gain. They conclude that NE_g and NP_g for growing meat goats exceeded the requirements previously published for dairy goats. They also suggested that N requirement for maintenance for growing goats was greater than the established recommendations. When goats were included in a mechanistic model [56] termed Cornell Net Carbohydrate and Protein System (CNCPS-S) that predicts nutrient requirements and biological values of feeds for sheep, Tedeschi et al. [57] suggested more data for goats are needed to account for specific differences in nutrition. Medeiros et al. [58] utilized Saanen male kids (n =41) in a slaughtered experiment and suggested that NE_m was 417 kJ/kg$^{0.75}$ EBW/d, while the ME_m was 657 kJ/kg$^{0.75}$ EBW/d. The efficiency of ME use for NE maintenance (k_m) was 0.64. The NE_g ranged from 7.4 to 9.0 MJ/kg of empty weight gain/d at 5 and 20 kg BW, respectively. Their study indicated that the energy requirements in goats were lower than previously published requirements by AFRC [40] and NRC [3] for growing dairy goats.

Results from a comparative slaughter experiment on Saanen goat kids (n = 54) suggested that it was not necessary to formulate diets with different energetic content for intact male, castrated male and female Saanen goat kids weighing from 5 to 15 kg [59]. They found no effect of gender on the energy requirements for maintenance and gain, and overall NE_m was 205.6 kJ/kg$^{0.75}$ EBW gain (EWG) or 170.3 kJ/kg$^{0.75}$ BW from 5 to 15 kg BW. The ME_m (calculated by iteration assuming heat production equal to metabolizable energy intake at maintenance) was 294.3 kJ/kg$^{0.75}$ EBW with a k_m of 0.70. As BW increased from 5 to 15 kg for all genders, the NE_g increased from 9.5 to 12.0 kJ/g EWG, and assuming k_g = 0.47, ME_g ranged from 20.2 to 25.5 kJ/g EWG. For growing male and female Saanen goats, ME_m was reported to be 412.4 kJ/ kg$^{0.75}$ BW, with an estimated energy use efficiency for maintenance of 0.627 [60]. During the growth phase, NE_g differed between the sexes; intact males, castrated males, and females with an average NE_g equal to 15.2, 18.6, and 22.7 MJ/kg EWG, respectively. They concluded that energy requirements for growth differed between the sexes and the difference was attributed to distinct NE_g and partial efficiency of ME utilization for growth during the late growth phase. Ferreira et al. [61] conducted a comparative slaughter experiment in castrated

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male Saanen goats weighing 20-35 Kg and reported that NE_m was 261.5 kJ/kg$^{0.75}$ BW, ME_m was 404.2 kJ/kg$^{0.75}$ BW, and the partial efficiency of the use of ME for NE was calculated to be 0.65. The minimal endogenous N losses were 262 mg N/kg$^{0.75}$ EBW, corresponding to a NP_m of 1.39 g/kg$^{0.75}$ BW. They reported that NE_g increased by 40% (from 12 to 17 MJ/kg EBW gain) and NP_g decreased by 3% (from 166 to 160 g/kg EBW gain) as the BW increased from 20 to 35 kg. Almeida et al. [62] proposed the possibility of using body composition to predict maturity as the mature weight is known to affect protein and energy requirement in goats.

The NE_m for non-pregnant and non-lactating pubertal female Saanen goats was suggested to be 52 kcal/kg$^{0.75}$ of BW [63]. The NE_g increased from 3.5 to 4.7 Mcal/kg of BW gain as BW increased from 30 to 45 kg. They concluded that that the guidelines of the major feeding systems for the entire growth phase may not be adequate for females at pubertal phase. For weaned male and female Saanen goats, Sex did not affect NE_g and NP_m (277.8 kJ/kg$^{0.75}$ BW/d and 2.98 g CP/kg$^{0.75}$ BW/d respectively), as well as NP_g (180.9 g/kg EWG) in Saanen goat kids [64]. However, castrated males and females had similar NE_g (varied from 12.6 to 17.9 MJ/kg EWG), but greater than intact males (varied from 9.74 to 10.7 MJ/kg EWG), as the BW increased from 15 to 30 kg. From the slaughter experiments, Teixeira et al. [65] concluded that maintenance requirement for F1 Boer × Saanen goat kids were greater than published values and growth requirements were driven by efficiencies of deposition and largely dependent upon changes in body composition. In their study, NE_m, ME_m and partial efficiency of use of ME_m for NE_m were 321.6 kJ/ kg$^{0.75}$ BW, 525.9 kJ/ kg$^{0.75}$ BW, and 0.61, respectively. The NP_m, MP_m and the partial efficiency of MP_m for NP_m were 2.43 g/ kg$^{0.75}$ BW, 4.41 g/ kg$^{0.75}$ BW, and 0.55, respectively. They also reported that the partial efficiency of the utilization of ME to NE for growth was 0.32, and the partial efficiencies of the utilization of ME for the synthesis of protein and fat were 0.19 and 0.59, respectively. Multiparous pregnant goats (n = 66) were utilized in a comparative slaughter experiment to determine the energy and protein requirements for the maintenance of pregnant dairy goats [66]. Days of pregnancy (DOP) did not affect NE_m or ME_m which were 197 and 315 kJ/kg EBW, respectively, and the efficiency of ME utilization for maintenance (k_m) was 0.63. The DOP did not affect NP_m estimated using the comparative slaughter technique (1.38 g/kg EBW) or using N balance (2.49 g/kg EBW). The MP_m estimated using the comparative slaughter technique was not affected by DOP and was 3.22 g MP/kg EBW. The efficiency of MP utilization for maintenance (k_m) was 0.43. The efficiency of ME utilization for pregnancy (k_p) increased with the progress of pregnancy and was 0.058, 0.10, and 0.19 at 80, 110, and 140 DOP, respectively. Similarly, the efficiency of MP utilization for pregnancy (k_p) increased with DOP and was 0.12, 0.21, and 0.43 at 80, 110, and 140 DOP, respectively. There was no evidence that pregnancy affected NE_m, ME_m, NP_m, and MP_m or k_m and k_p, which were also unaffected by DOP. However, k_m and k_p increased with pregnancy progress as a response to the physiological changes in pregnant females.

To investigate the effects of sex on the requirements for maintenance and efficiency of energy utilization in growing Saanen goats, Souza et al. [67] analyzed data (n=238) from 7 slaughter experiments and concluded that NE_m and ME_m estimated by the comparative slaughter technique were greater in males than in females (75.0 kcal/kg$^{0.75}$ EBW for males and 63.6 kcal/kg$^{0.75}$ EBW for females). Sex did not affected NE_M when degree of maturity was considered. Different sexes of Saanen goats have different energy utilization for growth (k_g =0.31 for castrated males and females, and 0.26 for intact males), but similar retained energy as protein (k_p = 0.21) and as fat (k_f = 0.80), and efficiency of ME utilization for maintenance (k_m=0.63). Using both the comparative slaughter technique (n = 185) and N balance method (n = 136) under a meta-analytical approach, Souza et al. [68] suggested that there was no evidence that sex affects the protein requirements for maintenance and efficiencies of protein utilization and proposes new equations for NP_m. The daily NP_m estimated was 1.23 g/kg$^{0.75}$ BW when using the comparative slaughter technique, while it was 3.18 g/kg$^{0.75}$ BW when using the N balance methos for growing Saanen goats. The MP_m estimated was 3.8 g/ kg$^{0.75}$ BW, the k_{pm} calculated as NP_m/MP_m was 0.33, and the k_{pg} calculated as NP_g/MP_g was 0.52. Santos et al. [69] proposed prediction equations to estimate microbial protein synthesis to be used for the calculation of rumen degradable protein (RDP) requirements from MP in sheep and goats. They found no differences to fit metabolizable crude protein (MCP) efficiency between sheep and goats, and suggested that MCP synthesis in the rumen can be predicted from energy intake using combined equations that encompass both sheep and goats. With the Akaike Information Criterion Index ranged from 2,755 to 3,007, they proposed that the prediction could be based on total digestible nutrients (TDN), digestible organic matter (DOM), or ME intake by the following equations: MCP (g/day) = 12.7311 + 59.2956 × TDN intake; MCP (g/day) = 15.7764 + 62.2612 × DOM intake; and MCP (g/day) = 12.7311 + 15.3000 × ME intake.

5. Macromineral Requirements in Sheep and Goats

A meta-analysis (n = 154 from comparative slaughter experiments, n = 160 from minimum endogenous losses experiments) was conducted to evaluate the effects of sex on the daily net requirements of calcium (NCa_m), phosphorus (NPh_m), potassium (NK_m), and magnesium (NMg_m) for maintenance in Saanen goats from 5 to 45 kg BW [70]. It was concluded that using the comparative slaughter technique, the results revealed that sex did not affect NCa_m, NPh_m, or NK_m (21.1, 22.8, and 4.0 mg/kg BW, respectively), but NMg_m of intact males was greater than castrated males or females (2.6 versus 1.4 mg/kg BW). When minimum endogenous losses method was used, sex did not affect the NCa_m, NK_m, or NMg_m (38.0, 25.2, and 7.4 mg/kg BW, respectively). They concluded that Mg requirement for maintenance should consider sex difference, but not Ca, P, and K requirements for maintenance in goats. They also pointed out that P requirements for maintenance were significantly lower than current feeding system recommendations. Daily maintenance requirements, calculated using the comparative slaughter technique, were estimated as 32.3 mg Ca, 30.8 mg P, 1.31 mg Mg, 8.41 mg K, and 5.14 mg Na/kg of empty EBW [70]. Net requirements for growth increased from 6.2 to 6.6 g Ca, 5.3 to 5.4 g P, and 0.29 to 0.30 g Mg and decreased from 1.20 to 1.07 g K and 0.65 to 0.59 g Na/kg EWG for kids from 20 to 35 kg BW. This study indicated that the net mineral requirements for Boer crossbred goat kids may be different from those of purebred or other genotypes, and more data are needed for goats in general [71]. The Ca, P, Mg, K, and Na requirements of Saanen goats were estimated from two experiments (n = 75 in comparative slaughter experiment, and n = 58 in growth trial) [72]. They reported that the daily net macromineral requirements for maintenance did not differ among the sexes, and the average values obtained were 35.4 mg Ca, 24.7 mg P, 2.5 mg Mg, 5.0 mg K, and 3.30 mg Na /kg BW/day. The net Ca, P, and Mg requirements for growth were not different among the sexes, but sex could affect net K and Na requirements for growth. They also reported that the net K requirements for growth (g/kg ADG) of intact males were greater and increased approximately 16%, whereas females and castrated males decreased approximately 11%, as BW increased from 15 to 30 kg BW. The net Na requirements for growth (g/kg ADG) increased 9.5% for intact males and decreased 22% for females when the goats grew from 15 to 30 kg BW. They concluded that sex affected net K and Na requirements for growth, but it did not affect net macromineral requirements for maintenance in Saanen goats.

Vargas et al. [73] compiled data from six comparative slaughter experiments (n= 209) and analyzed the effects of sex on the net requirements of growth for Ca (NCa_g), P (NP_g), Na (NNa_g), K (NK_g), and Mg (NMg_g) in Saanen goats from 5 to 45 kg BW, with or without the consideration of the degree of maturity. Without considering the degree of maturity, they reported that sex did not affect NCa_g, NP_g, and NNa_g. When the degree of maturity was considered, NCa_g and NP_g of intact males were greater than those of castrated males and females, and NNa_g of males (castrated and intact) was greater than that of females. The NCa_g and NP_g remained constant, whereas NNa_g decreased by 32% as BW changed from 5 to 45 kg. The NMg_g of castrated and intact males were greater than that of female goats, regardless of maturity. The NMg_g of castrated and intact males increased by 8% and 15%, respectively, whereas that of females decreased by 8% as BW ranged from 5 to 45 kg. They concluded that elucidation of sex effects on macromineral requirements for growth may be useful for improving the accuracy of recommendations for mineral requirements for dairy goats, and the consideration of maturity stage across sexes in should be considered [73]. There were indications that mineral requirements may be different between sheep and goats. Wilkens et al. [74] provided an overview of similarities and differences between sheep and goats. They concluded that ruminal Ca absorption and renal Ca excretion were not affected by dietary Ca supply in both sheep and goats,

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but goats were able to compensate for the low Ca availability and sheep could not. As a response to dietary Ca restriction, sheep had a smaller increase in plasma calcitriol but a greater increase in the circulating concentration of a bone resorption marker than goats. The Ca and P concentrations in ruminal and abomasal fluids and in saliva were reported being different between sheep and goats, with a greater salivary P secretion in goats than in sheep. In the peripartal period, differences in the contribution of gastrointestinal Ca absorption and bone mobilization to the maintenance of Ca homeostasis were observed in lactating and non-lactating animals of both species.

6. Estimating Nutrient Requirements

6.1. Physiological Functions and Classifications

Maintenance, growth, lactation, pregnancy, activity, breeding, and fiber growth are major physiological and/or productive functions considered for the determination of nutrient requirements for sheep and goats. In sheep, NRC [3] classifications of nutrient requirements include mature ewes, yearling farm ewes, yearling range ewes, rams (maintenance and prebreeding), growing lambs and yearling (early and late maturing). Mature ewes include four additional subclassifications: maintenance, breeding, gestation (early, late; single, twin and triplet), and lactation (early, mid, and late; single, twin, triplet or more) [3]. In goats, NRC classifications of nutrient requirements differentiate Angora goats from dairy and nondairy goats [3]. For dairy and non-dairy mature does, it is further classified to maintenance, growth, breeding, gestation (early, late; single, twin and triplet) and lactation (early, mid, and late; single, twin, triplet or more). For dairy and non-dairy mature bucks, it is classified as maintenance and prebreeding. For Angora goats, the classification include growing Angora kids (male and female), mature Angora males (maintenance and breeding), and mature angora females (maintenance, breeding, gestation and lactation). Gestation is further classified as early and late gestation and fetal size (single, twin and triplet); and lactation as early (single, twin) and late lactation.

A number of factors affecting nutrient requirements in sheep and goats have been described [3]. The list includes species, level of Intake, genotype, mature size, age, gender, body composition, use of tissue energy, activity, season, acclimatization, heat and cold extremes. Furthermore, parasitism can affect nutrient requirements of sheep and goats [3]. It is known that nutrient requirements in sheep and goats can be influenced by the environment [75]. As the effect of climate changes on the environment intensifies, it is likely that precisely estimation of nutrient requirements in sheep and goats will becoming even more important to minimized greenhouse gas emission and carbon footprint in the future.

6.2. Estimating Energy Requirements

Estimation of energy requirements in sheep and goats are based on two fundamental laws of thermodynamic and portion of Einstein's theory of relativity. Firstly, energy input must equal to energy output plus or minus any changes in body energy (Energy cannot be created or destroyed). Secondly, no transformation of energy is 100% efficient and the inefficiency is lost as heat (Entropy of the universe always increases). By applying these two principles it affords the equivalence between mass and energy and allow the conversion of body mass (kg) to energy (calories). Energy utilization by ruminants including sheep and goats can be partitioned into intake energy (IE), digestible energy(DE), metabolizable energy (ME), and net energy (NE) (Figure 1), and has been described and discussed [76]. A number of conversions have used in establishing energy requirement in sheep and goats [3]. Those include: DE (Mcal) = 4.4 TDN (kg), ME (Mcal) = DE (Mcal) x 0.82, estimate of heat production, conversion of ME to NE_M, conversion of ME to NE_g, conversion of ME to NE_L, and 1 Mcal = 4.184 MJ.

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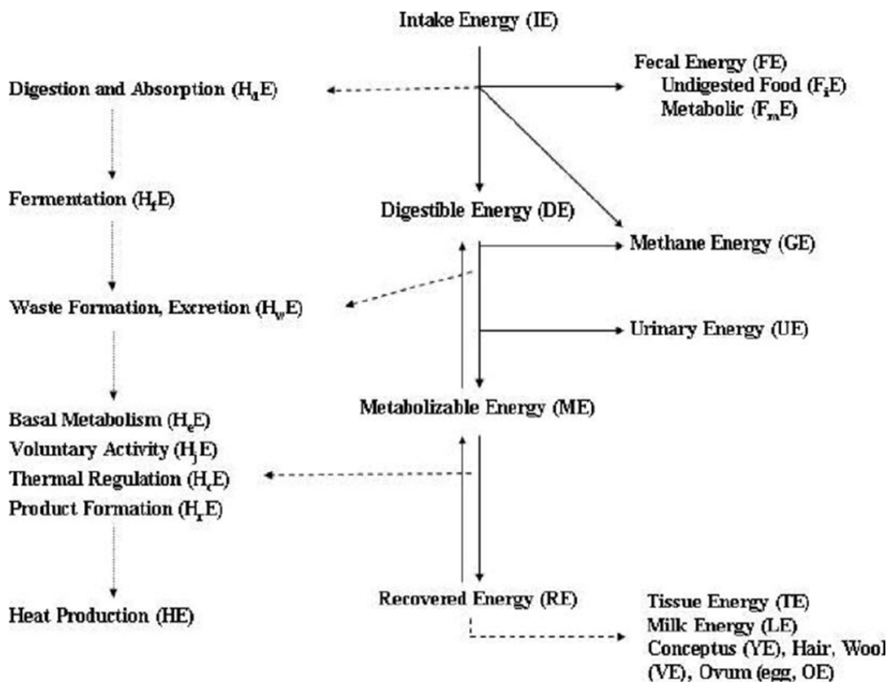

Figure 1. Schematic Diagram of Energy Utilization by Sheep and Goats (Modified from [76]).

6.3. NRC Equations for Predicting Energy Requirements for Sheep and Goats

A number of important equations have been used to estimate energy requirements in sheep [3]: For maintenance, unadjusted:

$$0.062 \text{ Mcal NE/kg SBW}^{0.75} \text{ ; } (\text{ME}_m \times 0.644 = \text{NE}_m) \quad (1)$$

For growth:

$$\text{NE}_g\text{, Mcal/d} = \text{ADG, kg} \times \text{TEC}_{avg}\text{; TEC}_{avg,}\text{ Mcal/kg} = (\text{TE}_{fin} - \text{TE}_{init})/(\text{FBW}_{fin} - \text{FBW}_{init})\text{;} \\ (\text{ME}_g \times 0.6 = \text{NE}_g) \quad (2)$$

For lactation:

$$\text{NE}_l\text{, Mcal/d} = (251.73 + (89.64 \times \text{MFC, \%}) + (37.85 \times (\text{MPC, \%})/0.95))) \times 0.001 \times \text{MY, kg/d} \\ \text{; } (\text{ME}_l \times 0.644 = \text{NE}_l) \quad (3)$$

A number of important equations have been used to estimate energy requirements in goats [3]: For maintenance, unadjusted:

$$101 - 149 \text{ kcal ME/kg FBW}^{0.75} \text{ ; } (\text{ME} \times 0.644 = \text{NE}) \quad (4)$$

For growth:

$$\text{ME}_g = 3.20 - 6.81 \text{ kcal/g ADG; ME}_{tg} = 8.89 \text{ kcal/g ADG (Angora); ME}_f = 37.5 \text{ kcal/g ADG (Angora)} \quad (5)$$

For lactation:

$$\text{ME}_l = 1.25 \text{ Mcal/Kg 4\%FCM} \quad (6)$$

where SBW is shrunk body weight, ME_m is metabolizable energy required for maintenance, NE_m is net energy for maintenance, NE_g is net energy for gain, ADG is average daily gain, TEC_{avg} is average energy concentration on a full body weight basis during the feeding period, TE_{fin} is final tissue energy, TE_{init} is initial tissue energy, FBW_{fin} final full body weight, FBW_{init} is initial full or unshrunk body weight, ME_g is metabolizble energy used for tissue gain, NE_l is net energy for lactation, MFC is milk fat concentration, MPC is milk true protein concentration, ME_l is metabolizable energy used for lactation, ME_{tg} is metabolizable energy used for nonfiber tissue gain, FCM is fat-corrected milk.

6.4. Estimating Protein Requirements

Nitrogen utilization in ruminants has been described [77]. Protein digestion in sheep and goats (Figure 1) is largely adopted from the model developed by Satter and Roffler [78], although there may be small difference in digestion kinectics such as rumen turnover rate between small and large ruminants [79,80].

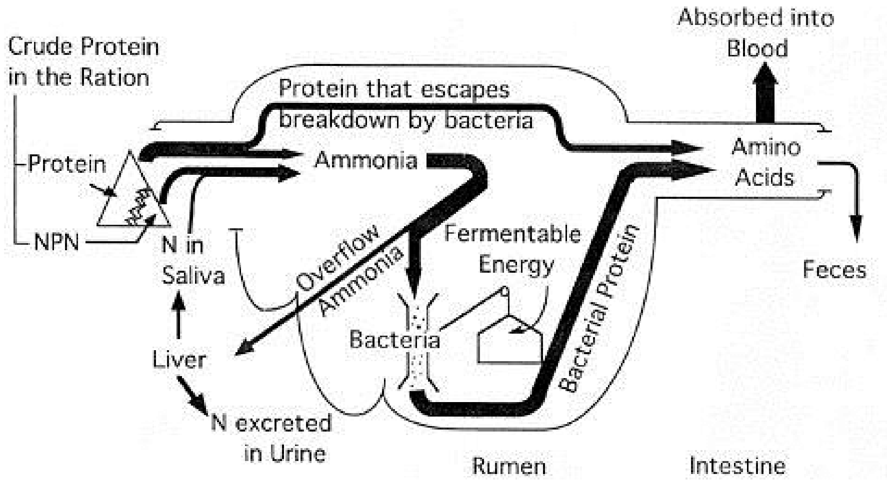

Figure 2. Protein digestion in Sheep and Goats (Adapted from [78]).

Intake protein (IP) is consisted of true protein and nonprotein nitrogen (NPN). Undegradable Intake Protein (UIP) is defined as 80% digestible and termed as Degradable Intake Protein (DIP) [3]. Digestible Protein (DP) is the difference between IP and Fecal Protein (FP) and is less useful to predict productive performance in ruminants due to microbial digestion and synthesis. Metabolizable protein (MP, true protein and AA that is digested postruminally) is the summation of UIP and Microbial Protein. Crude protein (CP) or IP is the summation of Ruminal Degradable Protein (RDP or DIP) and Ruminal Undegradable Protein (RUP or UIP). Therefore, RUP requirement = (MP required – MP bacteria – MP endogenous) / Diet RUP digestibility [3].

There are a number of assumptions used pertaining to the efficiency of conversation in estimate protein requirements in sheep and goats [3]. Efficiency of dietary MP for Maintenance (K_{pm}) is equal to 1.0. Efficiency of MP for Maintenance (K_{pm}) is similar for Metabolic Fecal Crude Protein (MFCP), Endogenous Urinary Crude Protein Loss (EUCP), and scurf CP. Range of K_{pm} from 0.67 to 1.00 is due to correction of MFCP for microbial CP. K_{pm} may vary with age and may be lower with greater intake. Efficiency of MP for Growth (K_{pg}) ranges from 0.5 [15] to 0.7 [81]. K_{pg} may vary with age, BW and body condition score. Efficiency of dietary MP for tissue gain in lactating goats is equal to 0.59. Efficiency of MP for Lactation (K_{pl}) varies: 0.58 [43], 0.59, 0.64 [33], 0.67 [82], 0.68 [39], 0.7 [81]. Efficiency of mobilized tissue protein for lactation ($K_{pl\text{-}t}$) is yet to be defined. Efficiency of mobilized MP for milk protein synthesis is equal to 0.69. Efficiency of MP for Fiber Growth (K_{pf}) varies: 0.26 [39], 0.48 [83], 0.5 [15], 0.6 [81]. K_{pf} may not be the same for wool sheep and angora goats and may be different between diet and mobilized tissue. Efficiency of mobilized MP for clean mohair fiber synthesis is equal to 0.61. Estimation of scurf and fiber crude protein requirements varied from 0.1125 g/kg $BW^{0.75}$ [39] to 0.2 g/kg $BW^{0.60}$ [82,84], as fiber production can be affected by season, breed, species, and frequency of shedding. Efficiency of MP for Pregnancy and Gestation (K_{ppreg}) varies: 0.33 [34], 0.4 [43], 0.65 [85], 0.70 [81], 0.85 [39,40]. K_{ppreg} may not be the same for sheep and goats and may be influenced by the development of mammary gland.

It is worthy to mention that evidences affecting the estimation of protein requirements have been emerging. Plant secondary metabolites can decrease activities of intestinal enzymes and interacting with epithelium lining that may ultimately affect the estimation of protein requirement [3]. Internal parasites can result greater use of AA for the synthesis of immunoglobulins and cytokines, increase

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replacement and repair of GI tract tissues with higher rates of liver protein synthesis can also affect the estimation of protein requirement [3].

6.5. NRC Equations for Predicting Protein Requirements in Sheep and Goats

A number of important equations have been used to estimate metabolizable protein requirements in sheep [3]:

For maintenance, plus fiber:

$$MP_m, g/d = (SF - CP_E/0.6) + (U\text{-}CP_E/0.67) + (F\text{-}CP_E/0.67) \quad (7)$$

For growth:

$$MP_g, g/d = NP_g/0.7; NP_g, g/d = ADG, g \times TPF_r \times 0.92 \quad (8)$$

For lactation:

$$MP_{l\text{-}d}, g/d = NP_{l\text{-}d}/0.58{:}\ NP_{l\text{-}d}, g/d = (10 \times MTPC, \% \times MY, kg/d) - (ADG, g \times TPF_r) \quad (9)$$

A number of important equations have been used to estimate protein requirements in goats [3]:

For maintenance, plus fiber:

$$MP_m, g/d = MFCP + EUCP + (0.2\ g/kg\ BW^{0.60}) \quad (10)$$

For growth:

$$MP_g, g/d = 0.290 g/g\ ADG\ (Dairy\ and\ Indigenous);\ MP_g, g/d = 0.404 g/g\ ADG\ (Meat);\ MP_g, g/d = 0.281 g/g\ tissue\ gain\ (Angora) \quad (11)$$

For lactation:

$$MP_l = 1.45\ g/g \quad (12)$$

For Fiber:

$$MP_{clean\ mohair} = 1.65\ g/g \quad (13)$$

where MP_m is metabolizable protein required for maintenance, $SF - CP_E$ is scurf and fiber protein, $U\text{-}CP_E$ endogenous urinary crude protein, $F\text{-}CP_E$ is metabolic fecal crude protein, MP_g is metabolizable protein available for gain and growth, NP_g net protein for gain, ADG is average daily gain, TPF_r protein concentration in tissue accreted or mobilized on an empty BW basis, $MP_{l\text{-}d}$ is dietary metabolizable protein required for lactation, $NP_{l\text{-}d}$ is net protein for lactation from the diet, MTPC is milk true protein concentration, MY is milk yield, MP_l is metabolizable protein used for lactation.

A simplified energy and protein requirements has been tabulated (Figure 3) for the purpose of comparison between sheep and goats. There are notable differences in both energy and protein requirements between these two species.

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Function	Species			ME Mcal/d	MP g/d
Maintenance	Sheep	Mature Ewes	50 kg BW	1.75	47
	Goat	Mature Dairy Doe	50 kg BW	2.25	53
		Mature Nondairy	50 kg BW	1.90	48
Growth	Sheep	Late Maturing	30 kg, 200 g/d	2.46	86
		Early Maturing	30 kg, 200 g/d	2.86	84
	Goat	Boer	30 kg, 200 g/d	2.49	120
		Dairy	30 kg, 200 g/d	2.74	97
Gestation	Sheep	Mature Ewes	50 kg, single	2.76	85
(Late)	Goat	Mature Dairy	50 kg, single	3.19	112
Lactation	Sheep	1.32 kg/d milk	50 kg, twin	3.85	170
(Early)		2.39 kg/d milk	90 kg, twin	5.54	237
	Goat	2.33 kg/d milk	50 kg, twin	4.41	205
		3.22kg/d milk	90 kg, twin	6.61	297

Figure 3. Comparison of NRC [3] energy and protein requirements between Sheep and Goats.

7. Limitations in Establishing Nutritional Standards

Because of a number of factors that has been identified to influence the determination of nutrient requirements, it is apparent that nutritional standards are relative, not absolute. It is targeted to a population but not to specific individual or a subset of group of animals, unless it is well defined at the beginning of the experiment. Nutritional standards can be determined through deduction or empirical methods. They are not always verified by additional animal experiments once established. These standards reflect the professional judgement or opinion of a group of experts during a particular period of time. In order to apply these standards effectively, the users must recognize the main sources of variation such as individual, genetic, climatic, dietary, age and physiological stages.

The basic methodology in the evaluation of nutrient requirements includes empirical and factorial approaches. Empirical method is based on observation or experience and is verifiable. Factorial method is related to a factor or integral parts of a factor. In the empirical method, nutritional requirements can be defined as the minimal amount of nutrients needed to maximize or minimize population responses for one or several performance criteria such as growth during a given time period [86]. In the factorial method, daily requirements can be calculated for an individual animal at a specific point in time by combining the estimated requirements for maintenance and production such as growth and milk production. The empirical method estimates optimal nutrient allowances from a population perspective, whereas the factorial method estimates the needs of a reference animal during a very short period of time [86]. There is always a need to reconcile the difference in nutrient requirements between empirical and factorial methods.

Advanced methodology in the evaluation of nutrient requirement can involve calorimetry in measuring energy intake and expenditure (direct and indirect), whole body dynamic non-invasive detection of body composition such as fat and lean mass imaging (magnetic resonance imaging, computed tomography, positron emission tomography, single photon emission tomography), system biology using mathematical and statistical modeling, and Integrating large data sets to interpret and understand complex physiological systems [5], and nutrigenomics. Application of Artificial intelligence (AI), with powerful machine and deep learnings in data analysis, has contributed to problem solving in agriculture, including predicting nutrient requirements in animals. Tedeschi [87] discussed the usefulness and limitation of mathematical modeling in predicting nutrient

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requirements in ruminants. He cautioned the less mechanistic modeling approaches such as AI for the replacement of mechanistic learning and system-thinking approaches.

8. Nutrigenomics and Nutrient Requirements

Advancement in molecular nutrition and especially nutrigenomics can have important impact on nutrient requirements. Molecular nutrition may be defined as a science concerned with the effect of nutrients and foods/food components on whole body physiology and health status at a molecular and cellular level [5]. Descriptive and mechanistic studies using state of the art epidemiology, food intake registration, genomics with single nucleotide polymorphisms (SNPs) and epigenomics, transcriptomics, proteomics, metabolomics, advanced biostatistics, imaging, calorimetry, cell biology, challenge tests (meals, exercise, etc.), and integration of all data by systems biology, will provide insight on a much higher level than today in a field we may name molecular nutrition research [5]. The concept of molecular nutrition research is broader than nutrigenomics.

The precise determination of molecular mechanisms underlying animal health and disease offers a great potential for promoting health, and lowering mortality and morbidity, and give to the rise of the science of nutrigenomics. Nutrigenomics is the study the effect of food constituents on gene expression and is broadly defined as the relationship between nutrients, diet, and gene expression [4]. It can identify molecular interaction between nutrients and other dietary bioactives with the genome. It also focus on the influence of genetic variation on nutrition and correlate gene expression or SNP (a DNA sequence variation occurring commonly within a population in which a single nucleotide — A, T, C or G — in the genome or other shared sequence differs between members of a biological species or paired chromosomes) with a nutrient's absorption, metabolism, elimination or biological effects. It has the potential to optimize and customize nutrition with respect to subject's genotype. It is promising and can be useful for disease prevention, health promotion and anti-aging. Although nutrigenomics in sheep and goats is considered as its infancy, there are recent contributions to the subject [88,89].

Nutrigenomics and other omics (genomics, epigenomics, transcriptomics, proteomics and metabolomics) and bioinformatics tools are poised to accelerate our understanding of the multiple levels of regulation induced in small ruminants by dietary nutrients during their utilization for milk, meat, wool, or reproduction [6]. Initial data indicate that the nutrigenomics approach may eventually lead to more precise management of goats and sheep, hence, helping to improve utilization of feed resources in a more optimal fashion [6], therefore, affecting the estimation of nutrient requirements. Nature largest gene depository resides in bacteria. Rumen microbes is an integrated part of nutrient digestion and utilization in sheep and goats. Understand of microorganism in the rumen can enhance the understanding of nutrient utilization and subsequently improve the precision of determination of nutrient requirements in sheep and goats. Total genetic composition of rumen microbes is consisted of core genome and accessory genome. Separation of commonly share genes (core genome) from strain specific genes (accessory genome) will certainly contribute to a better understanding of microbial interaction with nutrients. Precision nutrition is another arena that can deliver nutrients precisely to individual animal and have potential to meet nutrient requirements for the maintenance and production of meat, milk and fiver in sheep and goats. The Use of EID (ear tag that can be read by handheld reader) and software (feed formulation, livestock administration, reproductive optimization, quality management) make it possible to address individual needs of a particular animal. Readers are connected to the internet to process the data immediately for individual anima. The system recognizes individual properties of each animal and uses advanced technologies to optimize animal production. It enables the possibility to customize individual animal's nutritional needs and render application of nutrient requirements effective.

9. Conclusions

Nutrition is complicated. Defining nutrient requirements is a gateway to streamlining the mass nutritional information and enabling the practical application to animals. Therefore, it contributes to simplifying the complexity of nutrition at times. In spite of many variables, nutrient requirements of

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sheep and goats will continue to be an important focus for years to come. To justify the enormous investment, animal molecular nutrition or nutrigenomics will have to be linked more directly to the improvement of production efficiency via more precise prediction of nutrient requirement. To conserve resources and maintain long term sustainability, precision nutrition will continue to play a role. Meaningful research and discussion pertaining to implication of nutrigenomics and application of AI to nutrient requirements in sheep and goats can be useful in defining nutritional needs of not only the population but also individuals.

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